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RADIOACTIVITY SURVEYS

Stanley S. Johnson

Radioactivity surveys have been used since the late 1940's in the exploration for uranium and uranium-bearing rocks. From the early 1960's the airborne technique has progressed from the simple geiger counter and similar type instruments used in "anomaly hunting" to the highly sophisticated gamma-ray spectrometers with detectors having thousands of cubic inches in sensing crystal volume. Aeroradioactivity surveys are used increasingly for regional geologic studies and uranium exploration.

The use of radioactivity in geologic studies is based on the presence in rocks of the radioactive elements uranium and thorium, and a radioactive isotope of potassium. These elements and/or their isotopes emit gamma rays that can be detected with instruments such as geiger counters, scintillometers, electrometers, and spectrometers. Measurements of the radioactive properties of naturally occurring elements indicate that a low level of radioactivity is present in almost all rocks and minerals. The radioactivity of a particular rock and its weathered product is dependent upon the concentration of radioactive elements initially present and the change that the rock has undergone. Weathering and metamorphism are important in modifying the re-distribution of radioactive elements. In measuring radioactivity accurately, there are more variables than any other geophysical technique (Table 1).

RADIOACTIVITY

There are at least twenty naturally occurring elements that are radioactive, but only potassium, uranium and thorium are of use in radioactivity surveys. Other elements are either so rare or emit gamma rays that are so weak, or both, that they cannot be used.

There are four sources of gamma radiation that influence the reading obtained by crystal detectors in airborne survey equipment: (1) Cosmic radiation originates from outer space and gives low level, high-energy radiation. (2) Radioactive nuclides are produced by nuclear detonations ("fall-out"). Generally these isotopes will not interfere with the higher energy levels that the detectors are set to measure (Table 2). Except near the source of origin "fall-out" has not affected the contrast in radioactivity between adjoining lithologic units. (3) Radioactive nuclides occur naturally in the atmosphere, namely radon-222 and bismuth-214. (4) Natural radioactive nuclides are present in the surficial layers of soil and rock.

The use of radioactivity in geology and mineral exploration is based on several properties of gamma radiation: the penetrating power of gamma rays, the characteristic energy level of the individual elements, and the energy peak used for the detection of the individual element. To avoid interferences this peak must be isolated from adjacent peaks emitted by other

Table 1. Factors that should be considered in an aeroradioactivity survey.

Instrumentation
- size, efficiency, and speed of detector
- drift and temperature stabilization
- sensitivity
- calibration
- instrument and aircraft background
- elevation of survey above terrain

Atmosphere Conditions
- inversions (air)
- pressure (air)
- movement (air)
- precipitation
- fallout
- cosmic rays
- radon depletion (at surface)
- stability (air)
- moisture

Geology and Mineralogy
- topography and structural trends
- flight line direction and spacing
- cultural effects
- abundance of isotopes in ground
- solubility of uranium and thorium
- emanating power of soil and rock
- dis-equilibrium conditions in decay series
- thickness of radiation source
- burial of radiation source

Data Reduction and Compilation
- flight path recovery
- Compton stripping ratio
- background count
- live time
- Compton scatter
- altitude correction

Table 2. Thermonuclear fission products (Hansen, 1975).

Element	Isotope	Gamma-ray Radiation energy (MeV)	Half-life
Strontium	Sr- 89	———	50.5 day
Strontium	Sr- 90	———	27.7 yr
Yttrium	Y- 90	1.75	64.2 hr
Yttrium	Y- 91	1.19	57.5 day
Zirconium	Zr- 95	0.73	65 day
Niobium	Nb- 95	0.76	35 day
Ruthenium	Ru-103	0.56	40 day
Ruthenium	Ru-106	———	1 yr
Rhodium	Rh-106	1.56, 1.23, 1.07, 0.80, 0.74	1.3 min
Iodide	I-131	0.37	8.08 day
Cesium	Cs-137	0.66	26.6 yr
Barium	Ba-140	0.5	12.8 day
Lanthanum	La-140	1.6, 2.3	40 hr
Cerium	Ce-144	0.13, 0.08	285 day

Note: There are more than 100 radionuclides produced in a thermonuclear explosion by fission and neutron reactions. Some of the more prominent fission products are listed in this table.

elements in the energy spectrum. The gamma radiation measured for survey purposes comes from the daughter isotopes of uranium-238, thorium-232, and potassium (Table 3). The significant isotopes are bismuth-214 (from uranium-238), thallium-208 (from thorium-232) and potassium-40 (from potassium). They are used because of the distinctive energy peak that is emitted by each element.

In the case of uranium-238, only a few gamma rays are capable of detection. They are of such low energy and yield that they cannot be easily detected. Bismuth-214 is used for the detection of uranium because it has a sufficient yield (19 percent) of high energy gamma radiation at 1.76 MeV. Thallium-208 is used for detection of thorium-232 because it has a peak of high energy gamma radiation at 2.62 MeV that gives a yield of 100 percent. Potassium-40 has only one energy level at 1.46 MeV. The detection of isotopes at ground level and in the air is totally dependent upon the distinct energy peak emitted by each individual element (Table 3).

Gamma radiation recorded with a spectrometer is indicative of uranium and thorium only if these elements are in equilibrium with their daughter isotopes that emit the gamma rays (Hansen, 1975). Geologic conclusions (i.e. yield estimates of uranium and thorium content of the rock) based upon parent isotopic abundances derived from gamma spectral data must involve an assumption of equilibrium (Hansen, 1975). Within a few feet of the earth's surface, equilibrium between parent and daughter isotopes is uncommon because of weathering conditions and long half lives of these very mobile isotopes in the uranium-238 series. Equilibrium is common in the thorium-232 series because the daughter isotopes are not very mobile and their half-lives are short.

The concentration of isotopes available in the uranium and the thorium decay series is directly proportional to the half-life of those isotopes. A state of disequilibrium is present when all or part of one or more daughter isotopes or parent elements is physically removed from the decay series. Disequilibrium is quite common when radon-222, uranium-234, and radium-226, are removed from the series because of the solubility and mobility of these isotopes. The bismuth-214 measured by aerial surveys is a daughter of radium-226. Radon-222 is longer-lived and contributes to the greater potential for disequilibrium in the uranium-

238 series as compared with the shorter-lived radon-220 of the thorium-232 series (Table 3).

The intensity of radiation is proportional to the abundance of the isotopes present in the ground. The thickness of the contributing source also influences the intensity measured. The highest radiometric values generally occur over an exposed outcrop. In general, detection is limited to the upper foot of an outcrop area or overlying soil. However in loose soils the depth of detection may be somewhat greater, but generally less than two feet. Moisture plays an effective part in the masking or absorption of gamma rays. For all practical purposes, gamma radiation is effectively masked by 8 to 12 inches of rock, 1 to 2 feet of soil, or 1 to 3 feet of water. However, deeper sources of radiation may be detected due to the migration of radon-222.

Table 3. Natural radioactive decay series of uranium-238, thorium-232, and potassium.

Element[1]	Isotope (mass no. and symbol)	Approximate Half-Life
Uranium-238 Series		
X Uranium	$_{92}U^{238}$	4.51×10^9 yr
Thorium	$_{90}Th^{234}$	24.1 day
Protoactinium	$_{91}Pa^{234}$	6.8 hr
X Uranium	$_{92}U^{234}$	2.47×10^5 yr
X Thorium	$_{90}Th^{230}$	8×10^4 yr
X Radium	$_{88}Ra^{226}$	1600 yr
X Radon	$_{86}Rn^{222}$	3.8 day
Polonium	$_{84}Po^{218}$	3.1 min
Lead	$_{82}Pb^{214}$	26.8 min
X Bismuth	$_{83}Bi^{214}$	19.7 min
Polonium	$_{84}Po^{214}$	1.64×10^{-4} sec.
Lead	$_{84}Pb^{210}$	21 yr
Bismuth	$_{83}Bi^{210}$	5.0 day
Polonium	$_{84}Po^{210}$	138.4 day
Lead	$_{82}Pb^{206}$	Stable
Thorium-232 Series		
X Thorium	$_{90}Th^{232}$	1.41×10^{10} yr
X Radium	$_{88}Ra^{228}$	6.7 yr
X Actinium	$_{89}Ac^{228}$	6.1 hr
X Thorium	$_{90}Th^{228}$	1.9 yr
Radium	$_{88}Ra^{224}$	3.6 day
Radon	$_{86}Rn^{220}$	55 sec
Polonium	$_{84}Po^{216}$	0.15 sec
Lead	$_{82}Pb^{212}$	10.6 hr
Bismuth	$_{83}Bi^{212}$	60.6 min
X Thallium	$_{81}Tl^{208}$	3.1 min
Lead	$_{82}Pb^{208}$	Stable
Potassium-40 Series		
Potassium	$_{19}K^{40}$	1.26×10^9 yr
Argon	$_{18}Ar^{40}$	Stable

1. X Isotope of particular geological or geochemical interest.

RADIOACTIVITY IN ROCKS

The most abundant rock-forming minerals that contain radioactive isotopes are the potassium feldspars and micas. The primary unstable isotope in these rocks is potassium-40. Isotopes of uranium and thorium are found in accessory minerals such as zircon, monazite, sphene, apatite and others that are not as common. These accessory minerals contribute to the radioactivity of the rock and its weathered product. They may be a part of or exceed the background radiation from the feldspars and micas. The count per second rate from potassium-40 generally predominates over the count rates from either uranium or thorium in almost all rocks except the carbonates.

Granitic and pegmatitic rocks generally contain large amounts of potassium feldspar and mica and some accessory radioactive minerals. Thus relatively high levels of radioactivity are normally found over them. Most of the uranium and thorium in igneous rocks is contained in the accessory minerals zircon, apatite, and sphene. Pyrochlore, allanite, xenotime, uraninite, and thorite are highly radioactive and are accessories, but generally they are not evenly distributed. Generally potassium, uranium, and thorium content decreases in igneous rocks as they become less felsic in composition. Mafic rocks such as basalt normally lack potassium-bearing minerals and exhibit low radioactivity. Igneous rocks that are without mica and feldspar usually have very low concentrations of potassium. Ultramafic rocks such as dunite have the lowest content of radioactive minerals and display the lowest radioactivity levels of all igneous rocks.

Metamorphic rocks may display the same degree of radioactivity as the sedimentary, igneous, or other metamorphic rock from which they were derived, except where radionuclides have been introduced or removed during metamorphism (Tables 4 and 5). Gneisses and schists have moderate-to high-radioactivity. This variability in radioactivity is due to the degree of concentration of potassium-bearing and accessory minerals present in the rock.

In sedimentary rocks such as sandstone, limestone, and non-carbonaceous shale, most of the radionuclides are in the detrital particles. Generally, with the exception of black carbonaceous shale and arkosic sandstone, sedimentary rocks are low in radioactivity. Uranium enrichment in black shale results from the affinity of organic matter for uranium.

Uranium, through weathering and erosion, is easily leached from near surface rocks and soils. Leaching is accomplished because uranium is relatively soluble in oxidizing surficial environments. Because of this solubility uranium is released by oxidation of uraninite

Table 4. Relative radioactivity of selected rocks.

Rock Type	High	Moderate	Low
Igneous	X		
granite	X		
syenite	X		
pegmatite	X		
rhyolite	X		
diorite		X	
gabbro			X
basalt			X
diabase			X
ultramafic			X
Metamorphic			
gneiss (general)	<----------	---------->	
schist (general)	<----------	---------->	
marble			X
slate			X
quartzite			X
Sedimentary			
sandstone	<----------	----------	---------->
shale	<----------	----------	---------->
carbonates (pure)			X
siltstone	<----------	----------	---------->
Sediments			
clay	<----------	----------	---------->
black sands	X		

and other reduced uranium minerals, or by breakdown of apatite, sphene, and other accessory minerals. It is transported as an ion in solution until it encounters a reducing environment, an absorbent, or precipitant (Rose, 1977). By this process uranium is redeposited in many environments.

Although uranium is soluble in nearly all oxygenated surface waters, the lower oxidation state of many ground waters limits the solubility of uranium, especially the deeper waters in sedimentary rocks, where organic material and other reductants are present (Rose, 1977). Most surface and shallow ground waters are oxidizing and can thus dissolve uranium. The oxidizing capacity of water partially depends on the soil and rock types through which it flows and on the degree and type of topographic relief. As an example, areas of low relief, where gound waters move slowly, shallow ground waters may be reducing instead of oxidizing as previously mentioned. In most surface and ground waters, the uranium content correlates approximately with the total dissolved solids, conductivity, and bicarbonate concentration of the water (Rose, 1977).

Several uranium and thorium-bearing minerals such as zircon, monazite, xenotime and thorite are resistant to physical and chemical weathering and are not as mobile as other uranium-bearing minerals.

Table 5. Average radioelement content of rocks (Hansen, 1975).

	K^{40}ppm	Th ppm	U ppm	U/Th	Th/K^{40}	U[illegible]
Basaltic Rocks						
average	0.8	4.0	1.0	.25	5.0	1.2
range	0.2-2.0	0.5-10.0	0.2-4.0	—	—	—
Granitic Rocks						
average	3.0	12.0	3.0	.25	4.0	1.0
range	2.0-6.0	1.0-25.0	1.0-7.0	—	—	—
Shales						
average	2.7	12.0	3.7	.31	4.5	1.4
range	1.6-4.2	8.0-18.0	1.5-5.5	—	—	—
Sandstones						
average	1.1	1.7	0.5	.29	1.5	.46
range	0.7-3.8	0.7-2.0	0.2-0.6	—	—	—
Carbonates						
average	0.3	1.7	2.2	1.3	5.6	7.3
range	0.0-2.0	0.1-7.0	0.1-9.0	—	—	—

Other more or less insoluble uranyl minerals such as carnotite, autunite, uranophane, and torbernite, do not weather easily and are found near the primary uranium deposit.

RADIOACTIVITY MAPS IN GEOLOGIC MAPPING AND EXPLORATION

Radiometric contour maps and profiles are very useful to the geologist in field investigations. Radiometric contour maps have proved valuable in correlating lithologic units obscured by weathering. They can be used to confirm or correct existing geologic maps and to extend known geologic units into unknown adjacent areas.

Faults are often identified from characteristic radioactivity patterns. Relative low count rate values over a fault zone are probably due to the weathering and leaching of the radioactive minerals in the rock. High values can occur where the rock permeability has been increased because of fracture development. The increased permeability allows for the movement of ground water and the possible deposition of radioactive minerals. The radon-222 isotope may escape through fractures in rock formations as a gas. As it does not combine with other elements to form chemical compounds, it can migrate in solution freely through pore spaces, joints, and faults. Because of its short half-life of 4 days radon-222 moves in ground water only short distances (few hundreds of feet) from its parent (radium-226). Faults can be recognized by off-set of rock units which have a contrasting radioactivity pattern.

In exploration for radioactive and non-radioactive minerals, the spectrometer has proved to be a very useful geophysical tool. The occurrence of radioactive elements in rocks and minerals can be utilized in exploration for uranium, thorium, and some types of non-radioactive mineral deposits. The presence of uranium and thorium can lead to commercial deposits of minerals containing zirconium, yttrium, rare earths, tantalum, columbium and beryllium. Uranium is a common element in phosphate deposits and thus can be used in the exploration for phosphates. The spectrometer has proved very useful in the exploration for heavy mineral deposits containing ilmenite and other economic minerals. This is due to the presence of zircon, monazite, and sphene that accumulate in placer deposits and in the heavy mineral fraction of clastic sediments. The spectrometer may also prove useful in the exploration for porphyry copper as an alteration potassium halo occurs over some deposits of this type.

REGIONAL AERORADIOMETRIC SURVEYS IN VIRGINIA

The aeroradiometric surveys flown under contract for the Division of Mineral Resources utilize a four-channel, gamma-ray spectrometer detection equipment installed in a twin-engine aircraft. During the surveys the aircraft maintains a nominal elevation of 500 feet above ground at an average air speed of 140 miles per hour. At present the surveys are flown with a crystal detector having a total volume of 452 cubic inches. Traverse and tie-line locations are drawn on 1:24,000 scale U. S. Geological Survey topographic maps for use by the navigator and/or pilot in following designated flight lines. These are spaced at one-half mile intervals. The flight path of the aircraft is recorded by a 35-mm frame-type camera. The elevation of the aircraft above ground is measured by a continuously recording radar altimeter. Fiducial markings are made on all records and camera film to be used for identifying positions. Each survey is flown with simultaneously operating analog and digital acquisition systems.

The aircraft track is established by manual identification and correlation of the 35-mm tracking camera imagery with existing U. S. Geological Survey topographic maps. The airborne data tapes are processed by computer that decodes and translates the recorded data.

After preliminary checks, corrections, and editing (both by manual and computer means) of the spectral and ancillary data, the corrected and reformatted data are further processed to remove the effects of aircraft background, and the scattering of higher energy sources into the lower energy spectral windows.

Total system background radiation is determined by eliminating the contribution of terrestrial radiation. This contribution can be determined by flights made over large bodies of water at the 500-foot survey altitude. The background count rate, determined for each of the three energy window levels for potassium, uranium, and thorium, is subtracted from the observed count that effectively compensates for the combined contribution of both cosmic radiation and aircraft background.

Compton scattering effects are compensated for by using the spectral stripping method. The stripping ratios are determined from data taken over test pads containing known amounts of radioactive materials. The corrected radiometric data is then normalized to a constant terrain clearance of 500 feet. This is accomplished assuming the absorption of gamma rays varies expodentially with altitude. The various steps involved in the data processing procedure are depicted in Figure 1.

GAMMA-RAY SPECTROMETERS DETAILS OF OPERATION

The common airborne survey instruments currently being used to detect radioactivity are gamma-ray spectrometers with crystal detectors ranging in size from 400 to more than 2000 cubic inches. The crystals used in the detector are sodium iodide activated with thallium. At present this type of crystal is the most efficient and accurate in detecting and measuring gamma radiation in airborne surveys. Survey results are normally recorded on four-channel recording systems both in an analog and digital mode. The spectrometer and accessory equipment are generally flown in twin-engined aircraft at air-speeds sufficient to obtain good survey results. The air-speed is generally determined by the volume of the crystal system.

A spectrometer by definition separates gamma radiation into two or more energy levels. The detector absorbs the gamma rays present and converts them into light pulses. The light is received by photomultiplier tubes that convert the light pulses into electrical charges and amplify them. The amplified signal is proportional to the intensity of the light pulse. Electronic circuits separate the electrical charges into several classes based on the magnitude of the charge. The result is an energy spectrum based on the gamma radiation.

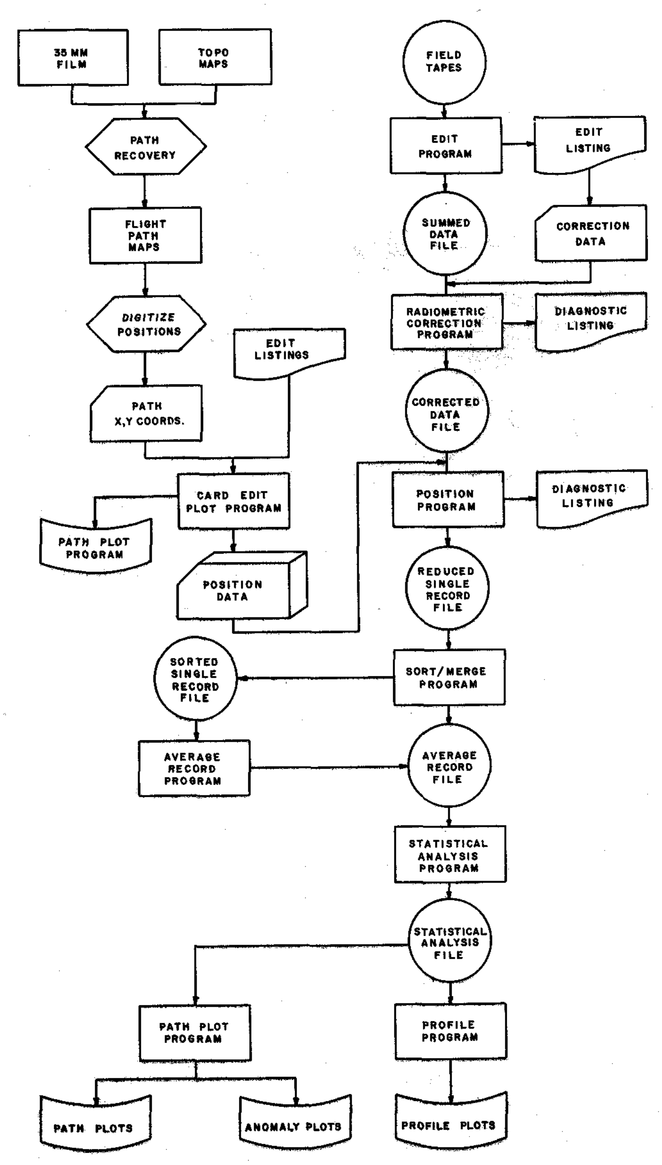

Figure 1. Data processing flow chart.

There are two basic types of spectrometers, the differential and integral. The integral type is used to measure only threshold or lower limits of a selected energy range. These spectrometers have a fixed upper limit. Where there is more than one isotope, a number of overlapping energy ranges are measured and identification is made by an indirect method of measuring the difference between energy thresholds. The differential type is used to measure the lower and upper limits of selected energy range. These spectrometers may be preset to select specific energy ranges or windows. This allows direct identification of the radioactive isotope. Where an instrument is constructed to preset several windows it is referred to as an multichannel spectrometer.

Modern airborne surveys generally use differential spectrometers with windows set for detection of the total count radiation (whole energy spectrum), and the energy levels for potassium-40 (1.37-1.57 MeV), bismuth-214 (1.66-1.86 MeV), and thallium-208 (2.41-2.81 MeV), separately.

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Rose, Arthur W., 1977, Geochemical exploration for uranium, *in* Symposium on hydrogeochemical and stream-sediment reconnaissance for uranium in the United States: United States Department of Energy, Grand Junction, Colorado, p. 303-347.

NEW PUBLICATIONS AND MAPS

(Available from the Division of Mineral Resources, Box 3667, Charlottesville, VA 22903; State sales tax is applicable only to Virginia addresses)

List Of Publications, 1979, No charge.

Directory Of The Mineral Industry In Virginia— 1978 by P. C. Sweet, 53 p., 1979, Price $0.78 ($0.75 plus $0.03 State sales tax.)

Raw materials and mineral commodities with corresponding names and addresses of mineral producers or processors are listed. An alphabetical list of company names is included as a helpful cross index.

Radiometric Maps—Central Virginia

A detailed aeroradiometric survey was flown 1978 over central Virginia from Andersonville southward to Madisonville covering a 480 square mile area. From

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traverses about one-half mile apart at a 500-foot altitude total counts per second and individual responses of potassium, thorium, and uranium were obtained and contoured maps produced. The actual location of some rock units can be interpreted from these survey maps. They are also useful in the exploration for uranium-bearing minerals.

The survey is a portion of a continuing effort to obtain geophysical measurements of rock characteristics throughout the Commonwealth. This is particularly important where soils obscure the underlying geological formations. Two adjoining surveys are available for northern and north central Virginia.

Individual radiometric maps at the scale 1:62,500 are available as ozalids for $2.00 each. For unfolded map orders of ten or fewer maps include an additional $2.00. Order by using following numbers: 74, Charlotte Court House NW; 103, Farmville NE, NW, SW; 104, Pamplin City. A composite of these is available at the 1:250,000 scale as an unfolded mylar copy for $15.00 each. Add 4 percent State sales tax to orders with Virginia addresses.

Aeromagnetic Map Of Virginia—Overlay

This see-thru map of magnetic values can be placed over the State Geologic Map as an aid in exploring for energy and minerals deposits. Folded copies are available for $1.30 ($1.25 plus $0.05 State sales tax); for unfolded copies add $2.00.

U.S.G.S. GEOLOGIC QUADRANGLES FOR SALE

The 25 U. S. Geological Survey geologic quadrangles which depict portions of Virginia are available from the Division sales office for $1.82 each ($1.75 plus $0.07 State sales tax). These show in color the type, location, and structural position of rocks in portions of the coal-bearing area of Southwestern Virginia. Geologic maps of the Milton and Quantico quadrangles are also for sale at the same price. A listing of these publications is available upon request.

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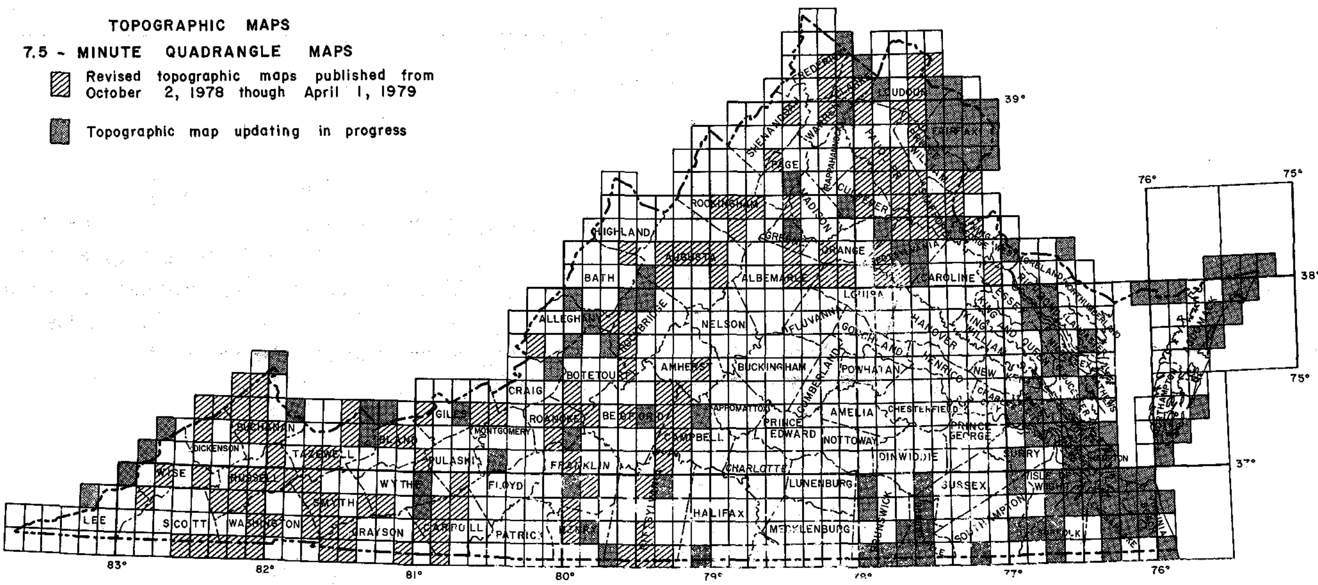

Revised 7.5-minute quadrangle maps published from October 2, 1978 through April, 1979. Each map available folded for $1.30 ($1.25 plus $0.05 State sales tax); if desired unfolded add $2.00 for orders of ten or fewer maps.

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Altavista
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Arcola
Arnold Valley
Ashby Gap
Augusta Springs
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Bastian
Bedford
Belmont
Bent Mountain
Big Stone Gap
Blacksburg
Bloxom
Brandy Station
Bridgewater
Broadford
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Brumley
Carbo
Castle Craig
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